Quantitative Chemical Mass Transfer in Coastal Sediments During Early Diagenesis

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LONG-TERM GOALS

The objectives of this study are: to measure rates and depths over which macroinvertebrates in selected functional groups transport sediment and create sedimentary structure; and, to derive quantitative mechanistic models for these property distributions. These observations and models will be integrated into mass-transport modeling of dissolved and particulate materials in marine sediments developed under this program. This work is a collaborative effort among Dr. Samuel Bentley (Louisiana State University), Dr. Carla Koretsky (Western Michigan University) and Dr. Yoko Furukawa (Naval Research Laboratory), originally started in 1997 under ONR322GG funding. We will focus on the synthesis of results during this phase.

OBJECTIVES

The specific objectives are:

1. Sub-millimeter characterization of the dynamics of redox fluctuation in the immediate vicinity of burrows in laboratory mesocosms and field test sites.

2. Millimeter-scale characterization of the response of sedimentary microbial community to the redox dynamics.

3. Fabric characterization of sediment constituents (pores, minerals, microorganisms and organic matter) and their interactions.

4. Model development to bridge the static and dynamic biogeochemical and fabric data to the net chemical mass transfer.

5. Millimeter- to centimeter-scale characterization of sedimentary particle dynamics in laboratory mesocosms and field test sites.

6. Model development to mathematically describe the macrofaunally-induced particle dynamics.

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14. ABSTRACT
The objectives of this study are: to measure rates and depths over which macroinvertebrates in selected functional groups transport sediment and create sedimentary structure; and, to derive quantitative mechanistic models for these property distributions. These observations and models will be integrated into mass-transport modeling of dissolved and particulate materials in marine sediments developed under this program. This work is a collaborative effort among Dr. Samuel Bentley (Louisiana State University), Dr. Carla Koretsky (Western Michigan University) and Dr. Yoko Furukawa (Naval Research Laboratory), originally started in 1997 under ONR322GG funding. We will focus on the synthesis of results during this phase.

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APPROACH

This report primarily addresses work conducted toward Objectives 3, 5, and 6, listed above. Field and laboratory observations of bioturbation and resultant fabric have been incorporated into preliminary models that describe emplacement and evolution of sedimentary fabric as functions of interacting event-sedimentation and bioturbation.

The particle bioturbation model is based on a time-dependent adaptation of the advection-reaction equation, wherein advection represents sedimentation, and reaction represents bioturbation. Conceptually, sediment deposited on the seabed initially possesses sedimentary fabric that is 100% physical in origin. Once an organism has "interacted" with physical fabric, whether by ingesting sediment or creating a burrow, that modified fabric becomes irreversibly biogenic (assuming no subsequent physical reworking, an admittedly flawed assumption). Thus, this model tracks the transformation of sedimentary fabric from physical to biogenic, rather than tracking sediment particles or a geochemical tracer. The relevant equations are:

$$\frac{\partial A}{\partial t} = -\left[\frac{\partial\, \omega(t) A}{\partial z}\right] - \left(\eta(z) A\right) \qquad \text{eq. 1}$$

Subject to the boundary conditions

$$\begin{aligned} &z = 0, J(A,t) = \omega A \\ &z = L_b, \frac{\partial A}{\partial z} = 0 \end{aligned} \qquad \text{eqs. 2, 3}$$

where z = depth in sediment, ω = burial rate (cm y^{-1}), L_b = maximum depth of bioturbation, A = horizontal area (limit of volume as $dz \to 0$) characterized by primary physical sedimentary fabric, J is flux of new unbioturbated sediment, and the depth-dependent volumetric bioturbation rate η (y^{-1}, or $cm^3\ cm^{-3}\ y^{-1}$) is described by

$$\eta(z) = \eta_0 \exp(-\alpha z), \qquad \text{eq. 4}$$

where α is a depth-attenuation coefficient.

WORK COMPLETED

Field data collection. Depositional history in our field areas have been assessed via core analyses ($^{210}Pb/^{137}Cs$ geochronology, X-radiography, granulometry, and multi-sensor core-logging). Benthic macrofaunal distributions and quasi-steady-state community bioturbation rates, depths, and styles (via mesocosm study, X-radiography and ^{234}Th, ^{7}Be, and ^{210}Pb tracer techniques) have been characterized for stations in Mississippi Sound and the Louisiana Chenier Plain. Results of these studies have been published in Bentley et al., 2002, and Keen et al., in press.

Particle dynamics modeling. The above model (equations 1-4) has been adapted to study the influence of particle mixing on fine-scale stratigraphy, with reference to preservation potential of event layers (Fig. 1). The model has been presented in Bentley and Sheremet (in press). The model has been used

to study preservation history of hurricane-generated sand layers in a regional core and modeling study (Keen et al., in press).

RESULTS

Model results (Fig. 1, and Bentley and Sheremet, in press) demonstrate that preservation potential of an event layer is strongly dependent on the subsequent deposition/erosion history, as well as the depth-distribution of bioturbation. This finding is not new, and has been demonstrated semi-quantitatively by a number of studies (Wheatcroft [1990] is an important example), including the STRATAFORM program (Wheatcroft and Borgeld, 2000; Bentley and Nittrouer, in press). However, no quantitative, predictive model has been developed previously that allows the simulating of sedimentary fabric for direct comparison with cores and outcrop.

In an application of the above model to study of the recent stratigraphic record, the formation, reworking, and preservation of two major hurricane event layers in a Gulf of Mexico coastal setting were studied through both core analyses and modeling (Keen et al., in press). The oceanographic and sedimentological processes that produced these event beds were simulated using a suite of numerical models: (1) a parametric cyclone wind model; (2) the SWAN third-generation wave model; (3) the ADCIRC 2D finite-element hydrodynamic model; (4) the Princeton Ocean Model; (5) a coupled wave-current bottom boundary layer-sedimentation model; and (6) a bioturbation-sedimentation model (Bentley and Sheremet, in press). Simulated cores from the Mississippi Sound region are consistent with the observed stratigraphy and geochronology on both the landward and seaward sides of the barriers, and confirm that both physical and biological processes (and their lateral variability) play critical roles in the post-depostional history of an event layer.

IMPACT/APPLICATIONS

The continued development of RT models to incorporate biologically created temporal and spatial heterogeneity will allow us to:

(1) predict the course of sedimentary structure evolution for the purpose of sediment stability, acoustic, mine burial, and permeability modeling.

(2) predict the mobility and bioavailability of contaminants following pollution events, dredging, engineering projects, remediation projects, or normal sedimentation for the purpose of site evaluation and planning.determine the parameters necessary for the particle suspension component of the coastal water optics model (e.g., shear strength of bioturbated seabed and organic carbon content of fluid mud and

(3) suspended sediments; Keen and Stavn, 1999) for the streamlined interpretation of optical signals from coastal waters.

TRANSITIONS

Models describing burrow formation (or genesis of sediment heterogeneity) and particle mixing (including rates of change at the sediment-water interface) will have direct relevance to studies of object burial and remote sensing of the shallow seafloor. Preliminary models derived from this work

are being used by the NRL-SSC Ocean Modeling Group to assess the preservation potential of fine-scale stratigraphy in the coastal ocean (Bentley et al., 2002; Keen et al., in press).

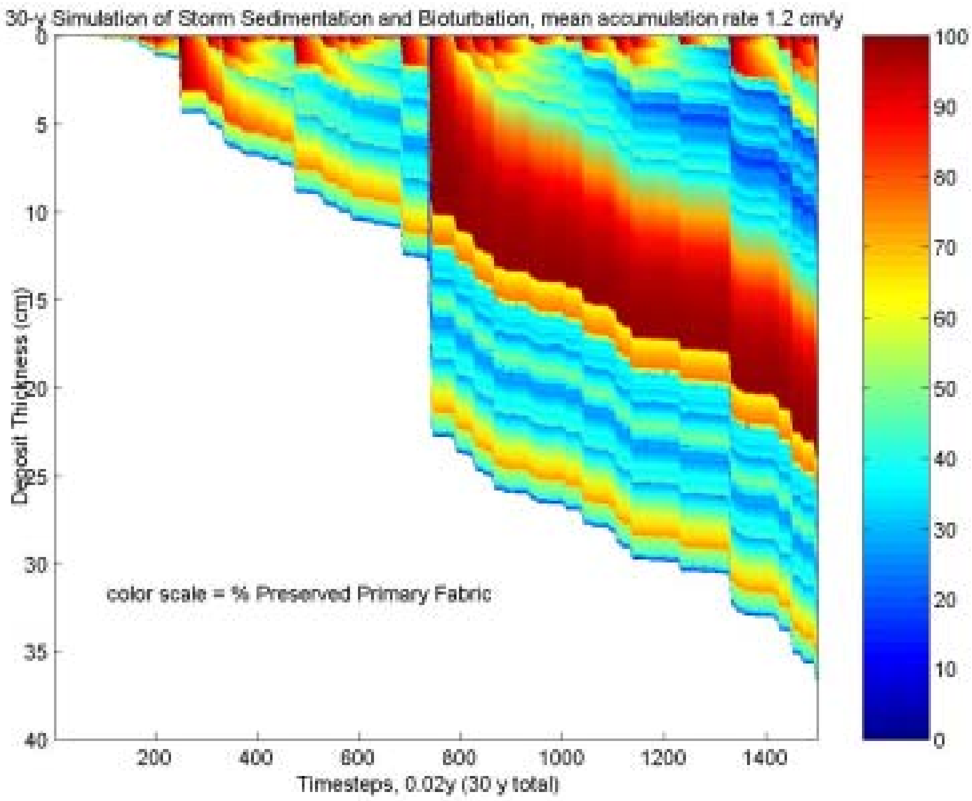

Figure 1. Thirty-year simulation of event-sedimentation and bioturbation using equations –4, with randomly generated depositional events that produce a time-averaged accumulation rate of 1.2 cm/y. Individual depositional events range from <0.1 cm to > 10 cm. The surface bioturbation rate, η_0 = 0.5 1/y, diminishes exponentially to ~0.005 1/y at depth L_b = 10 cm. Beds are deposited on the seabed with 100% physical fabric initially (red = 100% physical). Subsequent bioturbation replaces physical fabric with biogenic fabric (blue = 100% biogenic). It is evident that thick event layers (such as the layer deposited near timestep 700) have the highest preservation potential, and their deposition also enhances preservation potential for subjacent strata that are still within the zone of bioturbation. The depositional/bioturbation regime in this simulation is generally similar to the Eel Shelf mid-shelf depocenter(STRATAFORM study area), as described by Wheatcroft and Borgeld (2000) and Bentley and Nittrouer (in press).

RELATED PROJECTS

This is a collaborative effort between Dr. Samuel Bentley (Louisiana State University), Dr. Carla Koretsky (Western Michigan University) and Dr. Yoko Furukawa (Naval Research Laboratory),

originally started in 1997 under ONR322GG funding. Physical modeling efforts are also being coordinated with Dr. Tim Keen (NRL-SSC).

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